



ELECTROCHEMICAL DISCHARGE MACHINING FOR MICRO-CHANNEL CUTTING ON ELECTRICALLY NON-CONDUCTING MATERIAL

Aninda Das*, Puspendu Chandra Chandra & Sabyasachi Mukherjee*****

Assistant Professor, Department of Mechanical Engineering, Regent Education and Research Foundation, Bara Kanthalia, Sewli Telini Para, North 24 Parganas, Barrackpore, Kolkata, West Bengal

Cite This Article: Aninda Das, Puspendu Chandra Chandra & Sabyasachi Mukherjee, "Electrochemical Discharge Machining for Micro-Channel Cutting on Electrically Non-Conducting Material", International Journal of Advanced Trends in Engineering and Technology, Volume 2, Issue 2, Page Number 141-152, 2017.

Abstract:

The present research work is based on the detailed experimental observations on the performance characteristics of ECDM set-up during channel cutting operation. The electrochemical discharge machining (ECDM) process have been applied successfully for micro-channel cutting on electrically non-conducting material like glass irrespective of its chemical and mechanical properties and also the tool geometry. It has been found that the MRR and Width are increase with the increase of applied voltage at fixed electrolyte concentration. Also it is observed that the MRR and Width varies with respective to the nature of the tool. The least WOC is observed at applied voltage of 50 V with 15 wt% concentration of NaOH salt solution using curved tool.

Key Words: Electrochemical Discharge Machining, Micro Channel Cutting, Non Conductive Material, NaOH

1. Introduction:

Electrochemical Discharge Machining (ECDM) is an advanced hybrid machining process comprising the techniques of electrochemical machining (ECM) and electro discharge machining (EDM). The process is also referred as electrochemical spark machining (ECSM) process. The process is important since it can support a variety of materials including metals, ceramics, composites, alumina, glass, etc. The process has possible potential usage in the following areas:

- ✓ Micro-fabrication of miniature machine tools for micromachining
- ✓ Micro-fabrication of array of holes in SU-8 material (high aspect ratio, polymer, dielectric photo resist material) to fabricate micro-filters needed in micro-EDM process
- ✓ Micro-seam welding of copper plates and foils
- ✓ Fabrication of miniature components
- ✓ Heat treatment. Hence, electrochemical processes are being reconsidered for the micro-fabrication purposes. The study presents the use of ECDM for the micromachining purposes.

2. Literature Survey:

Yang et al. [1] stated that Electrical discharge phenomena in EDM occur in a very short time period and in a very narrow space, thus making both observation and theoretical analysis extremely difficult. In this investigation, the forming process of discharge craters in three dimensions has been simulated, and material removal mechanism in EDM has been analyzed using Molecular Dynamics (MD). The material removal mechanism in EDM has been explained in two ways; one by vaporization and the other by the bubble explosion of superheated metals. It was also found that the metal removal efficiency is 0.02–0.05, leaving most of the melted pool re-solidified. In addition, the influence of power density on the removal process has been investigated, and the results are showing that as the power density increases, the diameter and depth of the melted area increase, as does the metal removal efficiency. In this study, the forming mechanism of the bulge around discharge craters has also been analyzed, and it was found that bulge is formed due to two mechanisms i.e. (1) the flow of the molten material caused by the extremely high pressure in the superheated material, and (2) the accumulation of the ejected material on the bulge formed by the first forming mechanism. It has also been found that existence of micro pores in the work-piece material increases the depth of the discharge crater and melted area, thereby increasing the machining surface roughness. Simulation of the distribution of removed materials in the gap shows that some part of the removed material becomes debris ejected from the gap, while another part settles on the surface of the opposite electrode, and the last part returns to the surface of the electrode from which it has been ejected.

Jahan et al. [2] revealed that micro-EDM is an effective method of machining the extremely hard and brittle material such as Tungsten Carbide (WC). This study investigated the influence of major operating parameters on the performance of micro-EDM of WC with focus in obtaining quality micro-holes in both transistor and RC-type generators. Experimental investigations have been conducted with view of obtaining high-quality micro-holes in WC with small spark gap, better dimensional accuracy, good surface finish and circularity. In micro-EDM, the fabrication of micro-parts requires minimization of the pulse energy supplied into the gap which can be fulfilled using the RC-generator. It is observed that the RC-generator can produce

better quality micro-holes in WC, with rim free of burr-like recast layer, good dimensional accuracy and fine circularity. Moreover, the smaller debris formed due to low discharge energy in RC-type micro-EDM can be easily flushed away from the machined area resulting in surface free of burr and re-solidified molten metal.

Pham et al [3] showed that due to the high precision and good surface quality that it can give, EDM is potentially an important process for the fabrication of micro-tools, micro-components and parts with micro-features. However, a number of issues remain to be solved before micro-EDM can become a reliable process with repeatable results and its full capabilities as a micro-manufacturing technology can be realized. This investigation presents some recent developments in micro-EDM in its various forms (wire, drilling, milling and die-sinking) and discusses the main research issues. The investigation focuses on the planning of the EDM process and the electrode wear problem. Special attention is paid to factors and procedures influencing the accuracy achievable, including positioning approaches during EDM and electrode grinding.

Han et al.[4] stated that an RC pulse generator can easily generate a pulse on-time as short as a several dozen nanoseconds in micro-electro-discharge machining (micro-EDM), but its discharge frequency is low due to the time needed to charge the capacitor in micro-EDM, which has a strong negative effect on the pulse generator's working efficiency. Therefore, a new transistor-type isopulse generator has been developed for micro-EDM in this research. Evaluation of the machining characteristics proved that the transistor type isopulse generator is suitable for micro-EDM. The experimental results reveal that the transistor-type pulse train generator is unsuitable for micro-EDM due to its low removal rate: 80-ns and 30-ns pulse on-times of discharge current can be obtained by using the transistor-type isopulse generator developed in this research, and the removal rate of this generator is two or three times higher than that of the traditional RC pulse generator.

Bissacco et al [5] have proposed a new method of electrode wear compensation in micro EDM milling in this paper. Here EDM discharge is characterized by the statistical distribution of the population rather than individually. This basically relies on the discharge population characterization in terms of discharge energy and tool wear discharge. In addition periodic electrode wear length measurements have been performed for in-process wear discharge update. Following this approach TWR has been effectively compensated on the basis of discharge counting without the implementation of a pulse discrimination system. It has been shown that after 100µm of tool wear length, the TWD stabilizes at a value of 90µm³. The experiments have been done on a micro milling machine equipped with LSM to measure electrode wear and electrode diameter. Round bar made of WC of 300µm diameter has been used as tool electrode. Martensitic stainless steel has been used as work piece. This method can thus effectively be used for precise machining of free form geometries by µ-EDM milling. A validation has been done further to show the feasibility of the proposed approach.

Lee et al [6] have performed ultrasonic vibration assisted EDM with dc power supply between work-piece and electrode. In this hybrid machining process the MRR has been found a little above the individual processes (USM & EDM). But surface roughness value is about the same of USM. In ultrasonic machining ceramics, any increase in the amount of work/energy imparted to the ceramics in terms of the vibrating amplitude of the tool tip, the static load applied and the size of the abrasives will result in an increase in MRR, roughening of the machined surface and weakening in flexural strength. Spark erosion with ultrasonic frequency using a dc power supply instead of the usual pulsed power supply has been characterized. The pulse discharge is produced between tool electrode and work-piece. Vibrating sinusously with ultrasonic frequency the tool tip ejects the melted material and the erosion material easily exits the gap. The test results show that the MRR and the surface roughness value increase with the increase of voltage, current and amplitude of vibration.

Chern et al [7] have successfully developed a micro-punching machine that is capable of producing precision micro holes. The utilization of a solenoid as the power unit of the micro-punching machine and as the source of vibration is found to be a successful attempt. By applying the vibration machining technique, the efficiency of micro-EDM has been enhanced by reducing the machining time and improving roundness of the die opening and the punched micro-holes. Experiments to punch micro-holes with diameter of 100µm and 200µm on an SUS304 stainless steel strip with 100µm in thickness have been carried out successfully. Experimental results have shown that the performance of the developed novel micro-punching machine is satisfactory.

Pellicer et al [8] have investigated the influence of EDM parameters and electrode geometry on feature micro-accuracy in tool steel for mould fabrication purposes. A set of designed experiments with varying process parameters such as pulsed current, open voltage and pulse time and pulse pause time is carried out in H13 steel using differently shaped copper electrode. Micro dimensional and geometrical accuracies are the measures of the response. Artificial neural network and regression models have been constructed to capture the process parameters on the geometrical feature quality such as flatness, depth, slope, width and dimension variation between entrance and exit (DVEE). Agile manufacturing capabilities require fast response in workshops to cope with different demands in product geometrical features and qualities in fabricating mould. Therefore, direct machining of complex mould features using simple shaped machined electrodes with the electro discharge machining process, empowers the flexibility and capacity of the enterprises and dramatically reduces lead times

resulting in much more efficient production processes. In the case of machining geometrical features with characteristics dimensions in the order of few millimeters, the EDM process requires further understanding.

Maji and Pratihari [9] have attempted to model input-output relationships of an electrical discharge machining process based on the experimental data (collected according to a central composite design) using multiple regression analysis. Three input parameters, such as peak current, pulse-on-time and pulse-duty-factor, and two outputs, namely, material removal rate (MRR) and surface roughness (SR) had been considered for the said modeling. The value of regression coefficient was determined for each model. The performances of the developed models were tested with the help of some test cases collected through the real experiments and were found to be satisfactory. It had been posed as an optimization problem and solved using a genetic algorithm to determine the set(s) of optimal parameters for ensuring the maximum MRR and minimum SR. It was also formulated as a multi-objective optimization problem and a Pareto-optimal front of solutions had been obtained.

Tsai and Wang [10] have developed and compared models for prediction of surface finish in EDM process on aluminium and iron work-pieces based upon neural networks and aneuro-fuzzy network. They have done comparisons among different models developed with different training algorithms.

3. Objective of Present Work:

After successful completion of the past surveys, the objective of the present work is determined. For the enhancement of efficiency of machining and to fabricate the miniature components with good surface quality and high aspect ratio, technological development and modification of set up are basic requirement that has to be carried out. The following are the objectives for the present work.

- ✓ To study the basic characteristics of ECDM as well as to find out the problematic areas in these machining areas.
- ✓ To design and develop indigenously an experimental set-up, which can be used for ECDM for various profile cutting by controlling the 3 axis manually.
- ✓ To study the feasibility of these 3 machining process with various electrolytic solution for ECDM.
- ✓ To study the feasibility for ECDM in the newly developed set up for μ -drilling on glass with NaOH as Electrolyte with Straight and shaped tool and search out significant ECDM Parameters and its effective working range.

Moreover, present investigation into ECDM characteristics during micro-drilling of glass may be extended for using other and mixed electrolytes as well as other process parameters to meet the changes faced by precision manufacturing industries to fulfil present demand of micro-fabrication.

4. Experimental Set Up and Mechanisms:

As mentioned, ECDM is an extension of the ECM process. The electrolyte cell is similar to that used in ECM. In ECDM, anode is made up of inert material while cathode normally is made of copper. Dilute hydrochloric acid (HCl) is generally used as the electrolyte. When a voltage is applied to the cell in proper polarity, i.e., positive terminal to anode and negative terminal to cathode, reduction of electrolyte with liberation of hydrogen gas takes place at the cathode tip. This is similar to the ECM process. When the applied voltage is increased beyond a threshold value, hydrogen gas bubbles evolve in large number at the tip of the cathode and grow in size. Discharge occurs at the tip of the cathode. Machining takes place on the work-piece surface kept near the cathode tip where discharge occurs. In situ, synchronised, transient temperature and current measurements were performed. The experimental procedure and the set-up schematic are explained.

- ✓ Experiments are performed with graphite anode, 2 mm thick copper wire as cathode, and copper work-piece in 2.5 cm x 2.5 cm dimensions with 0.6 mm thickness. The working voltage is 155 V. Hydrochloric acid with 5 per cent concentration is used as electrolyte. Work-piece and cathode separation is of the order of 600 μ m.
- ✓ To sense the high, transient temperature of localized zone on the work-piece surface where discharge strikes, a pyrometer is used. Pyrometer model D-7441, Kohelberg, with a sensing temperature range of 815-1700 $^{\circ}$ C measures the temperature in a non-intrusive way. The pyrometer has been suitably modified for transient temperature measurements. Its Response time was experimentally determined using a step change in temperature and its suitability for this process has been established.
- ✓ To measure the temperature on the work-piece surface at the locations of 4 mm and 6 mm away from the discharge-affected zone, K-type thermocouples fabricated with smaller bead diameter to ensure smaller thermal mass and hence faster response to measure the temperature on the work-piece surface are used. Wires are wrapped in a sheath for better stability.
- ✓ To measure the temperature in the cell, immersion thermocouples provided with a special coating to withstand the harsh environment are used. These are placed at 16 mm and 26 mm from the discharge location in the ECDM cell.
- ✓ Current transients are measured using resistive shunt method. 1 resistor is connected in series with the cathode for this purpose.
- ✓ Discharge-affected region is examined using SEM.

- ✓ Pyrometer temperature transients and current transients are measured and stored using KIKUSUI 60 MHz, 4-channel digital storage oscilloscope. Study of transient temperature and current in synchronisation is the unique feature of the present study. A digital camera (Sony 10X Digital Mavica, MVC-FD7) is used for photographs of these stored waveforms. The K-type thermocouple output voltages are recorded using two digital multimeters (DM-375). A standard conversion chart is used to convert the voltage readings to temperature readings. Immersion thermocouples readings are displayed on digital thermometer.

General Principle:

- ✓ ECDM is a hybrid technology that combines the machining processes of ECM and EDM.
- ✓ It is a reproductive shaping process in which the form of the tool electrode is mirrored on the work-piece.
- ✓ It uses two electrodes: one is a cathode where the tool is connected and the other is an anode or an auxiliary electrode.
- ✓ The work-piece is placed just below the tool and along with the auxiliary electrode, is immersed in an electrolytic solution in a machining chamber.
- ✓ In the ECDM process the thermal erosive effects of electrical discharge (ED) action follows an electrochemical (EC) reaction.
- ✓ This electrochemical reaction helps in the generation of the positively charged ions and gas bubbles. These gas bubbles accumulate across the interface of the tool and the work-piece.
- ✓ The ED action takes place between the tool and the electrolyte across the gas bubble layers.
- ✓ If the applied DC power supply voltage is greater than the breakdown voltage of the insulating layer of the gas bubbles, a spark is initiated.
- ✓ If a non-conducting work-piece is placed in the closed vicinity of the electrical discharge, the material of the work piece is melted, vaporised and eroded due to the transmission of a fraction of spark energy to the work-piece.
- ✓ This raises the temperature of the region dramatically and a part of the molten portion of the work-piece is removed due to the mechanical shock resulting from the sudden phase change and the electrical spark discharge

Experimental Set Up:

To accomplish the objective of the project and to control the process parameters such as machining voltage, machining current, the feeding movement of work piece etc. The experimental set up includes the following sub systems:-

- ✓ Mechanical hardware system
- ✓ Electrolyte supply system
- ✓ Electrical power supply unit

Mechanical Hardware System:

The mechanical hardware system is one of the main parts of the set-up. This was developed to full fill the objective of the present research work. The hardware system consists of the following main elements such as:

- ✓ Main machine chamber
- ✓ Job holding unit
- ✓ Tool holding unit
- ✓ Tool positioning system (3 axis arrangement)
- ✓ Inter electrode gap control device
- ✓ Auxiliary electrode unit
- ✓ Tool feeding arrangement

Main Machine Chamber:



Figure 1: Main Machine Chamber

Main machining chamber made of Perspex and it is a rectangular box having dimension 380mm x 340mm x 270 mm with wall thickness 20mm. The proper material selection is one of the major and important tasks where manufacturing is concerned. In this research work Perspex is has been selected for the machining chamber because of the following properties

- ✓ High temperature Resistance
- ✓ Anti -corrosive
- ✓ Easily Machinable

Tool Holding Unit:

The tool holder is made of Perspex. It was made to serve the purpose for holding tool, which has been used to cut a profile on the work piece. The tool holder is screwed to a support rod. The tool holder is connected to the negative terminal of the power supply unit.



Figure 2: Tool Holding Unit

Inter Electrode Gap Control Device:

The tool can be moved Up and down to have a motion in Z axis by a rack and pinion system fitted on the tool post as shown in the fig.

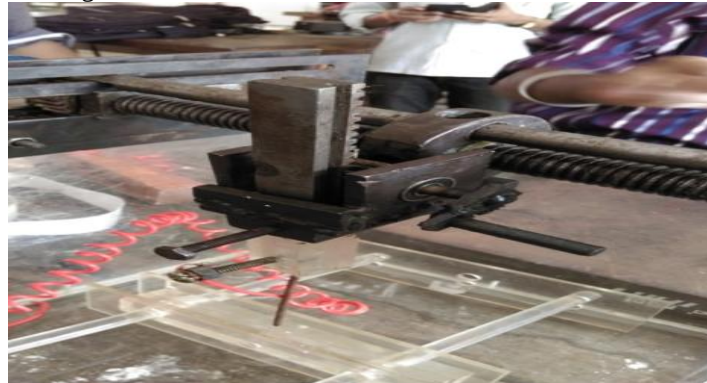


Figure 3: Inter Electrode gap control unit

Job Holding Unit:

An adjustable job holding unit is made of Perspex for holding the job of any dimension within the machining chamber for ECDM process.



Figure 4: Job holding device

Tool Positioning System -1:

The tool is held in the tool post which moves over a lead screw and has a motion in Y axis. Two support rods are used in both side of lead screw to keep the tool post perpendicular to the lead screw.

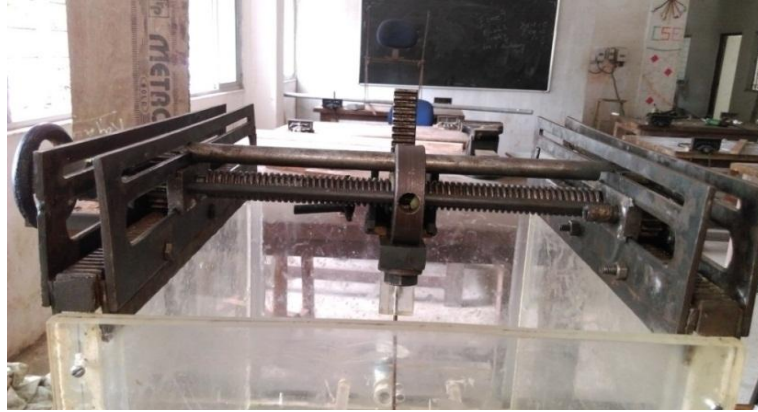


Figure 5: Tool Positioning System

Tool Positioning System -2:

The lead screw is moved by rack and pinion system which is held in the guiderails fitted at the top of the main machine chamber. The rack and pinion system moves the lead screw and hence the tool in X axis.



Figure 6: Tool Positioning System

Auxiliary Electrode Unit:

In ECDM process, the auxiliary electrode is a flat rectangular graphite plate of $100 \times 100 \times 10 \text{ mm}^3$, which is placed parallel to on which the job is placed. It is connected to the positive terminal of the D.C. power supply unit.

Electrical Supply Unit:

A variac is used as an electrical supply unit for ECM and ECDM machining operation but for EDM process a DC Pulse Generator/ Rotary Impulse Generator/ EDM Generator/ RC relaxation circuit may be used.



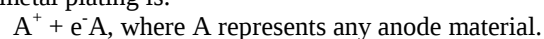
Figure 7: Variac

Reactions at the Cathode (or Tool):

The types of reaction at the cathode are:

- ✓ Plating of metal ions.
- ✓ Evolution of hydrogen gas.

The reaction for metal plating is:



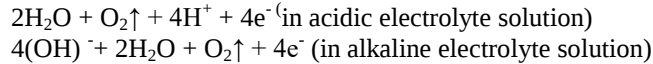
The reactions for hydrogen evolution are:
 $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\uparrow$ (acidic electrolytic solution)
 $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow 2(\text{OH})^- + \text{H}_2\uparrow$ (in alkaline solution)

Reaction at Anode (Auxiliary Electrode):

There will be two types of anodic reaction:

- ✓ Metal ions dissolution in the electrolytic solution and
- ✓ Oxygen gas evolution at the auxiliary electrode surface.

The anodic dissolution reaction is: $\text{A} \rightarrow \text{A}^+ + \text{e}^-$ (in acidic electrolyte solution). The oxygen evolution reaction is given as below:



The inter-electrode gap in the electrochemical discharge machining (ECDM) process is very large compared to the process of electrochemical machining (ECM). The material removal rate from the auxiliary electrode is very small because the very low current passes through a large inter-electrode gap.

Mechanism of Spark Generation:

A high voltage D.C. power supply of is applied between the tool (or cathode) and the auxiliary electrode (or anode). The tool is placed to 1 mm below the upper level of the electrolytic solution. The rate of generation of hydrogen gas bubbles is very high in the vicinity of the tool. As a result of heating of the electrolyte, some electrolyte is evaporated and steam is formed. The gas bubbles are usually low ionic positively charged bubbles. It has been found that when the bubbles generated due to electrochemically liberated H_2 and water vapour produced by ohmic heating at the tool-electrode interface, cover the maximum area of the tool electrode, dipped in the electrolyte, blanking between the electrode and the electrolyte takes place. As the voltage applied across the electrodes increased, the rate of bubble generation at the electrodes also increased. Under the normal conditions of bubble formation, with increase of the voltage supply, a critical or threshold voltage will be attained. When the threshold value of the voltage was reached, sparking started at the smaller electrode, further increase in the voltage increased the intensity of sparking. This sparking is not between electrodes, but from the tool to the electrolyte across the bubble layer. The voltage at which the sparking starts depends upon the types, concentration and conductivity of the electrolyte and the tool geometry. The smaller the diameter of the tool, the smaller will be the starting spark voltage. Violent sparking will be observed to take place if the voltage is increased further.

Mechanism of Material Removal:

There are micro-gaps between the tool and the work piece due to the surface irregularity present on both the surfaces of the tool and that of the work piece though they are touching each other. The electrolyte present in the micro-gaps is responsible for the formation of gas bubbles and steam generation. A low ionic bubble layer is formed in the micro-gaps at the surrounding tool surface. When the voltage gradient is sufficient to break down the gas bubble layer between the tool and the work piece, a conducting path is developed for spark discharge owing to the ionisation of the gas bubbles, which thereby causes the flow of a large amount of current. Each electrical discharge causes a focused stream of electrons to move with a very high velocity and acceleration from the cathode (or tool) towards the work piece and ultimately creates compressive shock waves on the work piece surfaces. The phenomenon is accomplished within a few microseconds and the temperature of the spot hit by electrons may rise to a very high value. As this high temperature is above the melting point of the work piece material, it melts and evaporates the material. The high pressure of the compressive shock waves create a blast, causing metallic vapour to form wear products in the shape of metallic globules, leaving craters in the work piece surface. The material removal from the work piece surface during electrical spark discharge is proportional to the pulse energy of the spark, which is released as heat during machining. Lesser tool wear takes place as low pressure compression shock waves are developed on the tool and the positive ions strike the tool surface with less momentum. Gas bubble formation and sparking phenomena as in the ECDM process are exhibited. Researchers have pointed out that rather than melting of the ceramics, the heat generated by the electrical sparking may cause the ceramic materials to spall. This phenomenon is known as thermal spalling, where the material removed is due to mechanical failure without melting. A temperature gradient is found to be established due to the sudden temperature change in the machining area of the ceramic materials. It is responsible for the generation of internal stresses that may be sufficient to overcome the bond strength of the ceramic grains, resulting in mechanical failure. In order to achieve effective and controlled material machining, various predominant input variables of the Micro-ECDM process are to be properly investigated and optimally controlled.

Mechanism of Tool Wear:

The removal of material takes place in the same way as the removal of work piece material. In electrochemical discharge machining process, an electrically non-conducting material is placed just below the tool along with the auxiliary electrode and is immersed in an electrolyte solution in machining chamber. The level of the electrolyte is maintained about 1 mm above the tool tip. When the area of tool electrode is about 100

times smaller than the auxiliary electrode the bubbles, which are evolved due to electrochemical reactions, greater at the surroundings of tool and forms a bubble layer. As the voltage is increased beyond a critical value i.e. the breakdown voltage of gas layer spark is initiated from the tip of tool with emission of light and releases heat energy. A fraction of this energy is absorbed by tool-electrode as conduction mode of heat transfer, which raises the temperature of tool. When the temperature of that portion tool-electrode exceeds the melting temperature the fusion of tool material takes place i.e. the tool starts to melt and sometimes it also vaporises. This removal of tool mainly depends on the area of the tool. If the dimension of the tool is small then the wear will be more as the current density increases. The erosion of tool material is also increased due to the increase in supply voltage and electrolyte condition.

Procedural steps for performing the experiments can be described as follows:

- ✓ Firstly clean the machining chamber properly with pure distilled water.
- ✓ The work piece and electrolyte was prepared for a particular concentration by mixing the required salt with distilled water of known amount.
- ✓ The work piece was clamped just below the tool tip and the tool tip was immersed 1mm below the upper level of the electrolyte.
- ✓ The desired inter-electrode gap was maintained by means of lowering or lifting the auxiliary electrode to the proper position using a screw-nut mechanism. The tool also can be moved up and down by a rotating lead screw to adjust the inter-electrode gap.
- ✓ The feed motion was applied to the work piece by a way of gravity feeding unit with an adjustable counter weight.
- ✓ The voltage was applied by controlling the variac. The readings of applied voltage and current were observed with the help of voltmeter and ammeter. Both readings were recorded.
- ✓ The level of electrolyte changed due to the boiling and evaporation. It was adjusted by means of regulating the flow of electrolyte in the machining chamber.
- ✓ The machining operation was performed for 10 minutes.
- ✓ After the machining operation, the machine was switched off and the work piece was removed and dried. The weight of the job was measured weighing machine (LC of 1×10^{-4} g). The Width of Cut (WOC), Machining Depth (MD)

The Material Removal Rate (MRR) of the micro-channel was calculated by using the following formula:

$$MRR = \frac{\text{Weight of Job Before Machining} - \text{Weight of Job After Machining}}{\text{Machining Time}}$$

Properties and Applications of Glass:

In this present study, micro-channel cutting operation was done on market purchased glass slide. It is the material, which has high refractive index, low density, significant strength and high insulation properties etc. glass is generally three types and they are Silica Glass, Vycor Glass and Borosilicate Glass. The silica glass was used for experimentation. The physical properties of silica glass are listed in the following table:

Table 1: Properties of Silica Glass materials

Properties	Silica Glass
Density (Kg/m^3)	2.52×10^3
Thermal Conductivity (W/m-k)	1.2
Thermal Expansion (K^{-1})	0.54×10^{-6}
Young's Modulus (N/m^2)	72×10^9
Tensile Strength (N/m^2)	50×10^6
Refractive index	1.518
Liquidus temperature ($^{\circ}\text{C}$)	1040

5. Experiments and Analysis:

The influences of process parameters such as Applied Voltage (V), Electrolyte Concentration (EC) on Material Removal Rate (MRR), Width of Cut (WOC), area and Machining Depth (MD) in micro-ECDM are analysed. Also a comparison is done based on the two different electrolytes, which were used in the experiment. Experimentation and analysis on Micro-ECDM performance characteristics using NaOH as electrolyte.

Table 2: Experimental results of NaOH as electrolyte.

S. No	Elect. Conc	Voltage (V)	Tool Shape	MRR (mg/hr)	Width of Cut (μm)	HAZ Area (mm^2)	Machining Depth (μm)
1	10	50	Straight	7.104	288.093	2.73482	195.816
2	10	55	Straight	7.963	253.154	2.12896	360.319
3	10	60	Straight	10.368	319.949	2.11483	166.584
4	10	65	Straight	12.251	643.964	2.69731	590.576
5	10	50	Curved	2.085	253.392	1.72461	102.584
6	15	50	Straight	10.863	264.139	0.72228	270.105
7	15	55	Straight	13.247	542.287	1.29491	322.128

8	15	60	Straight	15.6379	508.335	1.83657	299.423
9	15	65	Straight	16.816	524.387	1.07962	308.391
10	20	50	Straight	10.815	143.329	0.27228	346.504
11	20	55	Straight	19.814	340.216	1.28922	508.239
12	20	60	Straight	20.407	334.886	1.05416	389.92
13	20	65	Straight	27.257	264.526	1.85298	427.861
14	25	50	Straight	8.491	352.894	0.74519	184.889
15	25	55	Straight	11.412	350.856	0.71971	319.064
16	25	60	Straight	21.583	291.746	1.35141	257.718
17	25	65	Straight	26.418	405.831	1.23424	234.689
18	30	50	Straight	12.669	324.019	0.93589	213.346
19	30	55	Straight	12.863	316.853	0.92308	247.864
20	30	60	Straight	16.814	497.428	1.86437	362.984
21	30	65	Straight	34.656	625.416	1.96795	395.534

(i) Effects of Process Parameters on Material Removal Rate (MRR): The effects of applied voltage and electrolyte concentration on material removal rate for fixed inter-electrode gap when micro-channel is cut on glass with straight tools using NaOH salt solution as electrolyte are shown in Fig. 8. It shows that the material removal rate for NaOH electrolyte solution increases with the increase of applied voltage and the electrolyte concentration for fixed length of straight tools. The bubbles generation increases with the increase of voltage and electrolyte concentration since, the number of sparking increases with the increase of voltage and rate of electro-chemical reactions increase with increase of electrolyte concentration. At 65 V and 30 wt% electrolyte concentration the material removal rate is high. The material removal rate will be higher with increase of NaOH electrolyte concentration for curved tool but it increases with increase of 20 wt% of electrolyte concentration then decreases with increase of concentration for straight tool. This is because the conductivity of electrolyte is comparatively high at 20 wt% and it increases the rate of bubble generation. Fig. 8 shows that MRR for curved tool straight tool.

(ii) Effects of process parameters on Width of Cut (WOC): Fig. 9 exhibits the influence of applied voltage and electrolyte concentration on Width of Cut (WOC) in case of NaOH electrolyte for straight tool. The variation of width of cut as shown in Fig. 10 is similar with respect to different electrolyte concentrations. Generally, rate of sparking from bottom surface of tool as well as side surface of tool increases with the increase of both applied voltage and electrolyte concentration and thereby it increases not only MRR but also width of cut. The change of WOC is almost uniform for straight tool compared to curved tool. The width is minimum at applied voltage of 50 V, 20 wt% electrolyte concentrations but it reaches to the macro level at 30 wt% NaOH electrolyte concentration with applied voltage beyond 60V.

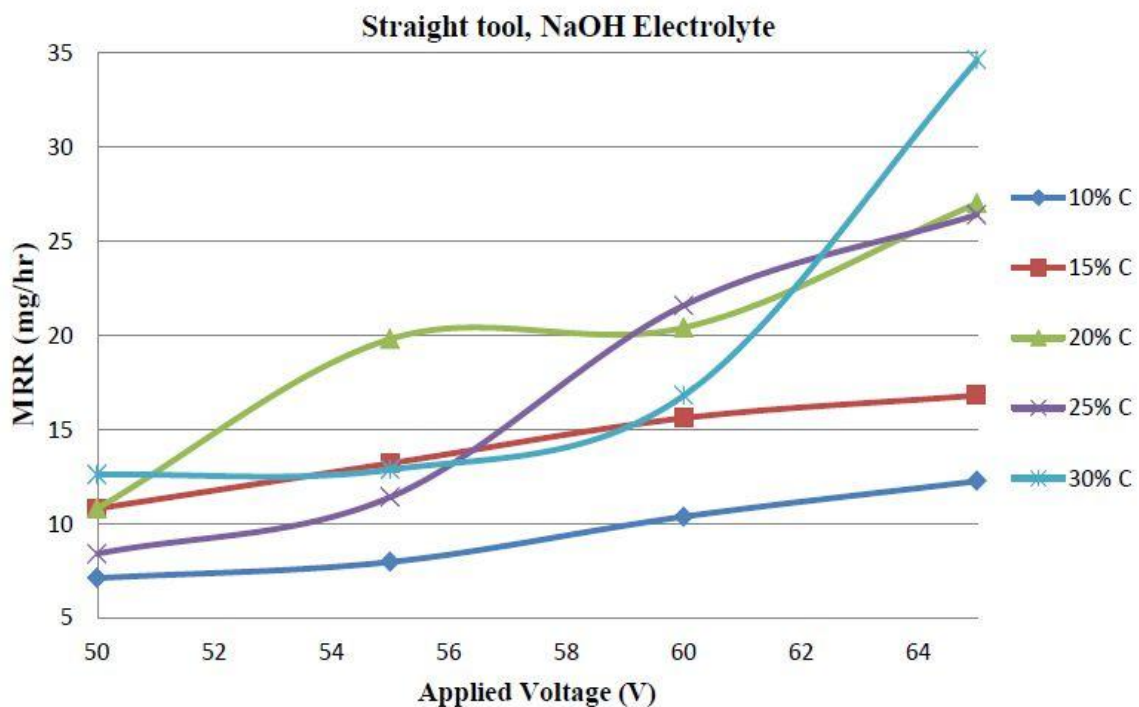


Figure 8: Effect of applied voltage and electrolyte concentration on MRR for straight tool

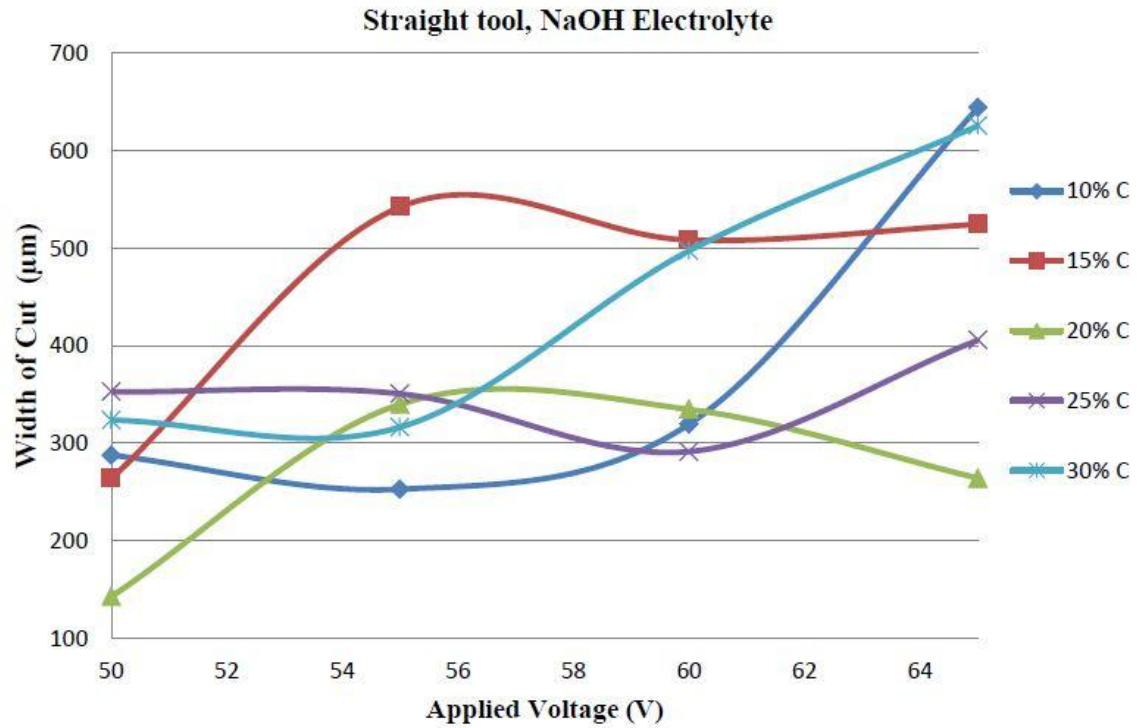


Figure 9: Effect of applied voltage and electrolyte concentration on width for straight tool

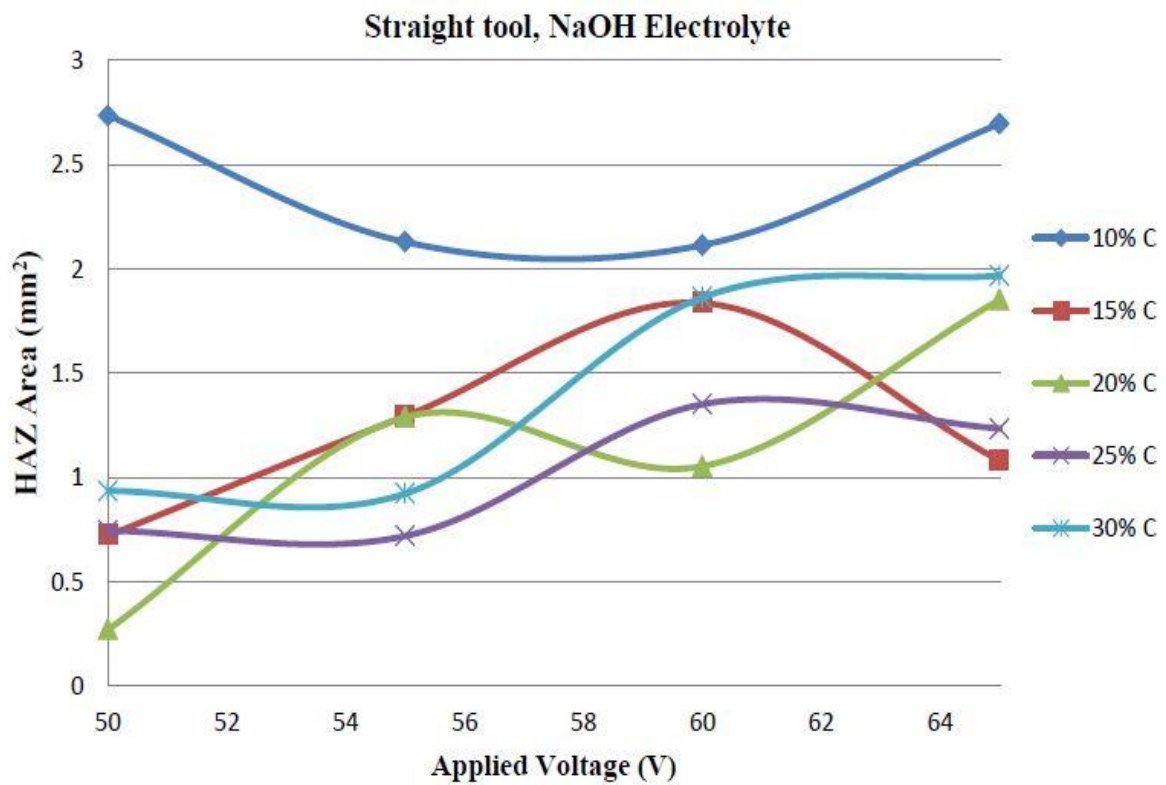


Figure 10: Effect of applied voltage and electrolyte concentration on HAZ area for straight tool

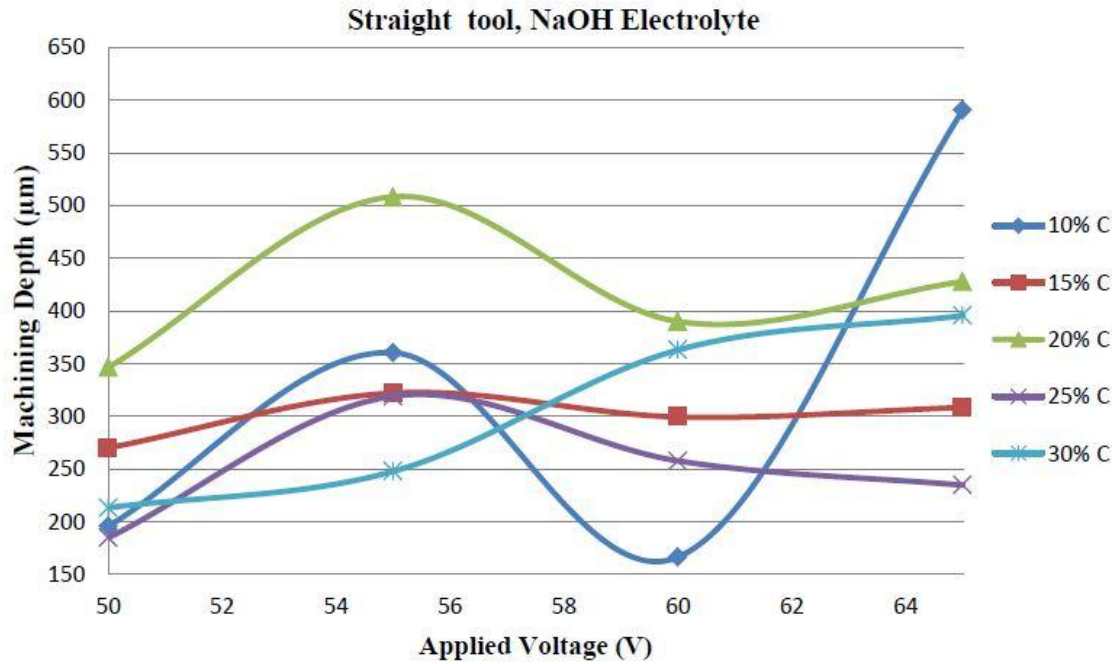


Figure 11: Effect of applied voltage and electrolyte concentration on machining depth for straight tool

6. Conclusions:

Within the limitation of the present research work the analysis based on the detailed experimental observations on the performance characteristics of ECMD set-up during channel cutting operation on in the present set of research the following general conclusions may be drawn:

- ✓ The study of the basic characteristics of ECMD as well as problematic area of ECMD technology has done successfully.
- ✓ The micro-electrochemical discharge machining (ECMD) process may be applied successfully for micro-channel cutting on electrically non-conducting material like glass irrespective of its chemical and mechanical properties and also the tool geometry. As observed the ECMD process reveals a tremendous prospective for micro-channel cutting on glass.
- ✓ From the present investigation it is found that the MRR and Width increase with the increase of applied voltage at fixed electrolyte concentration. Also it is observed that the MRR and Width varies with respective to the nature of the tool. The least WOC is observed at applied voltage of 50 V with 15 wt% concentration of NaOH salt solution using curved tool.

7. References:

1. Yang X, Guo J, Chen X, Kunieda M. Molecular dynamics simulation of the material removal mechanism in micro-EDM. Precision Engineering 35 (2011) 51-57.
2. Jahan M.P., Wong Y.S., Rahman M. A study on the quality micro-hole machining of tungsten carbide by micro-EDM process using transistor and RC-type pulse generator. Journal of materials processing technology 209 (2009) 1706-1716
3. Pham D T, Dimov S S, Bigot S, Ivanov A, Popov K. Micro-EDM—recent developments and research issues. Journal of Materials Processing Technology 149 (2004) 50-57.
4. Han F, Wachi S, Kunieda M. Improvement of machining characteristics of micro-EDM using transistor type isopulse generator and servo feed control. Precision Engineering 28 (2004) 378-385.
5. Bissacco G, Hansen H N (1), Tristo G, Valentincic J. Feasibility of wear compensation in micro EDM milling based on discharge counting and discharge population characterization-CIRP Annals-Manufacturing Technology (2011) 60: 231-234.
6. Lee T C, Zhang J H, Lau W S. Machining of Engineering Ceramics by Ultrasonic Vibration Assisted EDM Methods- Materials and Manufacturing processes (1998) 13:133-146
7. Chern G L, Engin Wu Y J, Liu S F. Development of a micro-punching machine and study on the influence of vibration machining in micro-EDM- Journals of Material Processing Technology (2006) 180: 102-109.
8. Pellicer N, Ciurana J, Ozel T. Influence of process parameters and electrode geometry on feature micro-accuracy in electro-discharge machining of tool steel- Materials and Manufacturing Processes (2009) 24: 1282-1289.

9. Maji K, Pratihar D K. Modeling of Electrical Discharge Machining Process Using Conventional Regression Analysis and Genetic Algorithms– JMEPEG (2011) 20:1121–1127.
10. Tsai, K.M. and Wang, P.J., (2001), “Semi-empirical model of surface finish on electrical discharge machining”, International Journal of Machine Tools and Manufacture, Vol. 41 pp.1455–1477.
11. Lin, J.L. and Lin, C.L., (2002), “The use of orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics”, International Journal of Machine Tools and Manufacturing, Vol.42, pp.237– 244.
12. Puertas, I, Luis, C.J. and Villa, G., (2005), “Spacing roughness parameters study on the EDM of silicon carbide, Journal of Materials Processing Technology, Vol. 164–165,
13. pp. 1590–1596.
14. Sarkar, S., Mitra, S. and Bhattacharyya, B., (2006), “Parametric optimisation of wire electrical discharge machining of γ titanium aluminide alloy through an artificial neural network model”, International Journal of Advanced Manufacturing Technology, Vol. 27
15. Mount A.R., Eley K.L., Clifton D. Theoretical analysis of chrono amperome tritransients in electrochemical machining and characterization of titanium 6/4 and in cone 1718 alloys, Journal of Applied Electrochemistry 30: 447 • }455, 2000.
16. Sorkhel S, Bhattacharyya B., Investigation for controlled electrochemical machining through response surface methodology-based approach, Technology, Volume, 15 February 1998, pages 200–207.
17. Jain, N. K., Jain, V. K., Optimization of Electro-Chemical Machining Process Parameters Using Genetic Algorithms, Machining Science and Technology, Volume 11, Number 2, April 2007, pp. 235-258(24).
18. Bhattacharyya B., Malapati M., Munda J., Experimental study on electrochemical micromachining, Journal of Materials Processing Technology 169 (2005) 485–492.
19. Bhattacharyya B., Mitra S., Boro A.K., Electrochemical machining: new possibilities for micromachining, Robotics and Computer Integrated Manufacturing, 18 (2002) 283–289.
20. Jain V.K., Kalia S., Sidpara A.M., Some aspects of fabrication of micro devices by electrochemical micromachining (ECMM) and its finishing by magneto rheological fluid, Int J Adv Manuf Technol (2012) 59:987–996.
21. Li Donglin , Zhu Di, Li Hansong, Microstructure of electrochemical micromachining using inert metal mask, Int J Adv Manuf Technol (2011) 55:189–194.
22. Nouraei S., Roy S., Design of experiments in electrochemical microfabrication, ElectrochimicaActa54 (2009) 2444–2449.
23. Nouraei S., Roy S. Electrochemical Process for Micropattern Transfer without Photolithography: A Modeling Analysis, Journal of the Electrochemical Society 155 (2) D97-D103 (2008).
24. Skoczypiec, S., Ruszaj A., Application of ultrasonic vibration to improve technological factors in electrochemical machining of titanium alloys.
25. Sun J. J., E. J.Taylor, Gebhar L.E., Zhou C. D., Eagleton J. M., Renz R. P. Investigation of Electrochemical Parameters into an Electrochemical Machining Process, NAMRI/SME, Volume XXVI, 1998.
26. Dhobe S. D., Doloi B., Bhattacharyya B., Surface characteristics of ECMed titanium work samples for biomedical applications, Int J AdvManufTechnol(2011)55:177–188.
27. Das A. K., Saha P., Machining of circular micro holes by electrochemical micromachining process, Adv. Manuf. (2013) 1:314–319.
28. S. Tandon, V. K. Jain, P. Kumar and K. P. Rajurkar, Investigations into machining of composites, International Journal of Precision Engineering, 227-238, 1990.
29. V. Raghuram, T. Pramila, Y. G. Srinivasa and K. Narayanasamy. Effect of the circuit parameters on the electrolytes in the electrochemical discharge phenomenon, Journal of Materials Processing Technology, 52, 301-318, 1995.
30. Basak, A. Ghosh. Mechanism of spark generation during electrochemical discharge machining- A theoretical model and experimental verification. Journal of Materials Processing Technology.62, 46-53, 1996.
31. Basak, A. Ghosh. Mechanism of material removal in electrochemical discharge machining: a theoretical model and experimental verification. Journal of Materials Processing Technology.71, 350-359, 1997.